Journal of Stored Products Research 47 (2011) 204–209

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

# Flameless catalytic infrared radiation used for grain disinfestation does not affect hard red winter wheat quality☆

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ARTICLE INFO

*Article history:*
Accepted 19 November 2010

*Keywords:*
Infrared radiation
Wheat quality
Rheological properties
End-use qualities

ABSTRACT

The effects of a bench top flameless catalytic infrared emitter at temperatures and times used for disinfesting grain on the physical, chemical, rheological, and end-use qualities of wheat were evaluated in the laboratory. The test weight of wheat was unaffected when 113.5 and 227.0 g of hard red winter wheat were exposed for 45 or 60 s to infrared radiation. However, a slight drop in kernel moisture increased kernel hardness, but these effects were reversed when the wheat was tempered prior to milling. Flour, shorts, and bran yields, and chemical properties (protein and ash) of these fractions from untreated wheat and infrared-treated wheat showed minor differences that were inconsequential. Mixograph and bake test results did not reveal any consistent adverse effects of infrared radiation on the quality parameters studied. Our results show that infrared treatments that provide effective control of stored-grain insects do not affect the physical, chemical, rheological, and end-use qualities of hard red winter wheat.



## 1. Introduction

The most common and damaging insect species associated with wheat stored on farms and at elevators in Kansas and neighboring states are the lesser grain borer, *Rhyzopertha dominica* (F.); rice weevil, *Sitophilus oryzae* (L.); and red flour beetle, *Tribolium castaneum* (Herbst) (Reed et al., 1991, 2003). Activity of all three species of insects has also been observed outside farm bins (Dowdy and McGaughey, 1994) and at elevators (Dowdy and McGaughey, 1997). Both *R. dominica* and *S. oryzae* immature stages complete development inside kernels of wheat and contribute to insect fragments when wheat is milled.

Surveys have shown that grain protectants are more commonly used to manage insect populations in wheat stored on the farms, especially in Kansas, whereas the fumigant phosphine is routinely used on wheat after it leaves the farm (Storey et al., 1984; Reed and Pedersen, 1987; Kenkel et al., 1992; Martin et al., 1997). Insects in stored wheat are managed primarily by chemical means, and non-chemical methods are underutilized (Martin et al., 1997). The use of chemicals, especially traditionally used organophosphate grain protectants such as malathion and chlorpyrifos-methyl have resulted in the development of insect resistance (Hagstrum and Subramanyam, 2006). New and innovative technologies need to be constantly explored for effective disinfestation of wheat, because of problems associated with pesticide residues, development of resistance in insects, and to meet quality demands of domestic and foreign buyers. Furthermore, limited pest management options are available for managing insect pests in stored organic wheat.

Infrared (non-ionizing) radiation is electromagnetic energy with wavelengths (0.075–1000 μm) longer than visible light (380–750 nm) and shorter than microwaves (0.1–100 cm) (Penner, 1998). This energy is transferred to whatever material absorbs it, and the absorbed energy causes a measurable change in the material's temperature. This radiant "heat energy transfer" depends on how readily the molecularly bonded atoms in the material convert the incident radiant energy into molecular vibration energy that in turn raises the temperature of the absorbing material and its surroundings. Water readily absorbs mid-infrared radiant energy by the symmetric and asymmetric stretching of molecular bonds between oxygen and hydrogen atoms and by bending of the same bonds (Wehling, 1998). The wavelengths most associated with these absorption mechanisms fall between about 2.8 and 7 μm.

The unique nature of absorption of infrared radiation by water has been used for rapid drying of cereal commodities, especially wheat (Bradbury et al., 1960) and rice (Schroeder, 1960; Schroeder and Rosberg, 1960; Faulkner and Wratten, 1969; Pan et al., 2008). In

☆ Mention of trade or proprietary names in this publication does not imply an endorsement by Kansas State University or the USDA.

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0022-474X/$ – see front matter 
doi:10.1016/j.jspr.2010.11.005

addition to drying commodities, infrared radiation has been used successfully to kill immature stages and adults of stored-grain insects (Tilton and Schroeder, 1963; Cogburn, 1967; Cogburn et al., 1971; Kirkpatrick and Tilton, 1972; Kirkpatrick et al., 1972; Tilton et al., 1983). In all these tests, infrared radiation sources used natural gas or propane combusted over ceramic panels in the presence of oxygen. These gas-fired radiation sources were of high intensity producing 14.07 kW/h (48,000 BTU/h) resulting in temperatures close to 926° C. The infrared radiation wavelength produced was 2.5 μm; small amounts of carbon dioxide and water vapor were also produced. These high intensity infrared emitters had an open flame and may not be suitable for use in dusty grain-handling facilities due to explosion hazards.

Catalytic Industrial Technologies, LLC, in Independence, KS, USA, has developed a proprietary flameless infrared technology for various drying applications (http://www.catalyticdrying.com). In flameless infrared emitters, propane or natural gas chemically reacts with oxygen in the presence of a platinum catalyst delivering radiant energy in the 3–7 μm range resulting in temperatures below 500 °C. Temperature to start the self-sustaining catalytic reaction is achieved by an electric heating element embedded in the emitter unit. The catalytic infrared heaters are environmentally friendly, and since they do not use any flame, these heaters do not produce any $NO_x$ or CO. The co-products of catalytic oxidation–reduction reaction are infrared radiation, carbon dioxide and water vapor. Pan et al. (2008) reported the catalytic emitter to be effective in drying and disinfesting paddy rice.

In the laboratory, we evaluated a bench top catalytic infrared emitter from Catalytic Drying Technologies LLC using 113.5 or 227.0 g of wheat exposed for 45 or 60 s at a distance of 8.0 or 12.7 cm from the emitter in killing all life stages of three insect species associated with organic hard red winter wheat. These species included two internal developers, *R. dominica* and *S. oryzae*, and one external developer, *T. castaneum*. The tests showed catalytic infrared radiation to be effective in killing all life stages of the three species, especially when the grain attained temperatures between 108° and 113 °C during a 60 s exposure (Khamis, 2009; Khamis et al., 2010). However, very little information is available in the literature on the adverse effects of these short exposures to infrared radiation on the physical and chemical properties of wheat. Tilton et al. (1983) did not report the initial moisture content of wheat, but observed a 0.4–0.6% loss after exposure to infrared radiation for 30–45 s, and the final temperatures attained by wheat ranged from 52 to 56 °C. The lack of information on the adverse effects of infrared radiation on wheat quality, and the positive results obtained in our laboratory, prompted us to explore the effects of infrared radiation on wheat's physical, chemical, rheological, and end-use qualities.

## 2. Materials and methods

Uninfested, organic, hard red winter wheat was procured from Heartland Mills in Marienthal, KS, USA. Wheat (113.5 or 227.0 g) was placed in separate 0.45-L glass jars with wire mesh screens and filter paper lids. These jars were incubated at 28 °C and 65% relative humidity (r.h.) for two weeks to equilibrate the wheat moisture to 12% (wet basis) in the Stored Product Insect Research and Education Laboratory (SPIREL), Department of Grain Science and Industry (GSI), Kansas State University (K-State), Manhattan, KS, USA. A large number of such jars were set up for exposure to infrared radiation. Each grain quantity was exposed to a bench top flameless catalytic emitter at 8.0 or 12.7 cm from the emitter surface for either 45 or 60 s (see Table 1 for treatment combinations). For each treatment combination, a total of 2 kg was accumulated by repeated exposures at the parameters specified. The only two treatment combinations that were not used because of poor insect kill in our previous laboratory tests (Khamis, 2009; Khamis et al., 2010) were 113.5 and 227.0 g of wheat exposed at 12.7 cm from the emitter for 45 s, as these treatments produced less than 90% mortality of *R. dominica*, *S. oryzae*, and *T. castaneum* life stages. Each treatment combination was replicated three times. The control treatment consisted of six 2 kg lots of wheat that were not exposed to infrared radiation.

**Table 1**
Treatment combinations used for exposing organic hard red winter wheat to flameless catalytic infrared radiation to assess wheat quality.

| Infrared treatment ID | Factors evaluated: | | |
|---|---|---|---|
| | Grain quantity (g) | Distance from emitter (cm) | Exposure time (s) |
| A (Control) | –[a] | 0 | 0 |
| B | 113.5 | 8.0 | 45 |
| C | 227.0 | 8.0 | 45 |
| D | 113.5 | 8.0 | 60 |
| E | 227.0 | 8.0 | 60 |
| F | 113.5 | 12.7 | 60 |
| G | 227.0 | 12.7 | 60 |

[a] The control treatment consisted of a 2 kg lot that was not exposed to infrared radiation. For treatments B–G, 10–20 lots of 227.0 or 113.5 g were exposed to infrared radiation to obtain the necessary 2 kg sample for flour extraction and quality tests. Each treatment was replicated three times.

A 1-kg wheat sample from each treatment combination was used to determine test weight (bulk density) using the Winchester bushel apparatus (AACC Method 55–10). Kernel moisture (% wet basis) and kernel hardness index (a dimensionless index) of infrared-exposed and unexposed wheat before and after tempering to 16% moisture, prior to milling, were determined using the Perten 4100 Single Kernel Characterization System (SKCS, Perten Instruments North America Inc., Springfield, IL, USA), based on developments by Martin et al. (1993). The SKCS tests 300 kernels per sample and provides frequency distribution data for kernel hardness and moisture.

Infrared-exposed and unexposed wheat were tempered by addition of water to achieve 16% moisture content for 16 h. The tempered wheat was weighed and milled in a Buhler mill (Buhler MLU-202, Uzwil, Switzerland) in the GSI department, K-State. The gaps in the roller mills were adjusted according to the recommendation of the manufacturer. Before milling, the machine was warmed for 30 min by milling wheat. The feed rate was 130–150 g of wheat/min. The break and reduction flours were combined. Shorts were collected and resifted through a 132 μm aperture cloth sieve for 2 min to extract any residual flour. The flour extracted from shorts and previous flour fractions was blended for 5 min using a laboratory blender. Total flour, bran, and shorts yields, and yield loss were calculated and reported on a percentage basis based on the weight of the original wheat and the weights of each of the three fractions. The ambient temperature and relative humidity during milling were 14 °C and 40%, respectively.

The flour size distributions of wheat exposed to infrared radiation and control wheat samples were determined using a Malvern Mastersizer 2000 (Malvern Instruments Ltd, Worcestershire, UK), which uses light diffraction to determine the size of dry powders. This analysis was conducted by NanoScale Corporation, Manhattan, KS, USA. Two samples of each treatment combination were analyzed to provide information on 10%, 50% and 90% of the particles below a certain diameter.

The Agtron M-45 Color Meter (Agtron Inc, Reno, NV, USA) in the GSI department, K-State was used to determine bran contamination of all flour samples. The Agtron M-45 color meter is a direct-reading reflectance spectrophotometer designed to measure the relative spectral qualities of product samples. The meter, set on the green wavelength (546 nm), is calibrated using a 67 calibration tile for the

**Table 2**
Changes (mean ± SE) in kernel hardness and moisture content of untreated and infrared-treated wheat before and after tempering.

| Treatment | Before tempering | | After tempering | |
|---|---|---|---|---|
| | HI[a,b] | Moisture (%)[b] | HI[a,b] | Moisture (%)[c] |
| A | 77.1 ± 0.6b | 11.5 ± 0.1a | 74.9 ± 0.6bc | 15.4 ± 0.0 |
| B | 82.2 ± 1.4ab | 10.4 ± 0.1bc | 80.4 ± 0.5a | 15.3 ± 0.2 |
| C | 79.1 ± 3.2ab | 10.9 ± 0.1ab | 72.5 ± 0.5c | 15.2 ± 0.1 |
| D | 85.3 ± 0.3a | 9.8 ± 0.1c | 78.7 ± 1.4ab | 14.9 ± 0.4 |
| E | 85.9 ± 0.8a | 10.4 ± 0.1bc | 78.0 ± 0.7ab | 15.7 ± 0.1 |
| F | 82.9 ± 0.8ab | 10.3 ± 0.0bc | 78.9 ± 1.6ab | 15.4 ± 0.4 |
| G | 79.7 ± 2.3ab | 10.2 ± 0.6bc | 75.2 ± 0.7bc | 15.3 ± 0.4 |

[a] HI, kernel hardness index.
[b] Means within a column followed by different letters are significantly different ($P < 0.05$, REGWQ test).
[c] Means among treatments were not significantly different from one another ($P > 0.05$, one-way ANOVA).

"0% Relative Spectral Reflectance" reading and a 97 calibration tile for the "100% Relative Spectral Reflectance" reading. When using the green wavelength light, relative spectral reflectance is inversely proportional to the degree of bran contamination of flour (Gillis, 1963; Shuey, 1975). The higher the relative spectral reflectance, the brighter is the flour (low ash).

The AACC 44-15A air oven method was used for determining the moisture content of bran and shorts, while ash and protein were measured using the AACC 08-01 muffle furnace method and AACC 46-30 Leco combustion method, respectively (AACC, 2000). The moisture content, protein, and ash of flour were determined using a Perten DA 7200 near-infrared analyzer (Perten Instruments, Springfield, IL, USA). Protein and ash contents were reported on a 14% moisture basis. A Megazyme total starch enzymatic assay kit (Megazyme International Ireland Ltd., Wicklow, Ireland) was used to measure residual starch in bran (AACC Method 76.13). The flour was subjected to the AACC Method 56-81B to determine the falling number (AACC, 2000), a measure of enzyme activity or sprout damage to wheat. The AACC Method 54-40A was employed to determine gluten strength by the resistance of dough to mixing with pins, and flour water absorption using a mixograph. AACC Method 10-10B was used to determine bake water absorption, mixing time, and loaf volume. The falling number test, mixograph, and bake tests were done at the Wheat Quality Laboratory, GSI department, K-State.

Data on each of the physical, chemical, and rheological properties obtained were subjected to one-way analysis of variance (ANOVA) to determine significant differences among the seven treatments at $\alpha = 0.05$ using the GLM procedure (SAS Institute, 2002). Means among treatments were separated using the Ryan-Einot-Gabriel-Welsch Multiple Range (REGWQ) test. None of the data were transformed for analysis because Levene's test (SAS Institute, 2002) showed variances among treatments to be homoscedastic for each of the quality factors. Kernel moisture, kernel hardness frequency distributions, before and after tempering, was plotted using SigmaPlot software (Scientific Graphing Software, version 11, Systat Software, Chicago, IL., USA).

## 3. Results

The mean test weight of wheat that was not exposed to infrared radiation was 79.6 kg/hl, and those samples exposed to infrared radiation ranged from 79.9 to 81.0; differences in test weights among the treatments were not significant ($F = 2.84$; df = 6, 14; $P = 0.0504$). The kernel hardness and moisture before and after tempering showed some variation among treatments that was significant (Table 2). The hardness of kernels exposed to infrared radiation was consistently and slightly higher than wheat that was not exposed to infrared radiation, and differences among treatments were significant ($F = 3.74$; df = 6, 14; $P = 0.0197$). The kernel moisture in infrared radiation treatments was 0.6–1.7% lower than untreated wheat ($F = 9.52$; df = 6, 14; $P = 0.0003$). Except for treatment C, kernel hardness after tempering also showed differences among treatments ($F = 8.14$; df = 6, 14; $P = 0.0006$), but unlike hardness values prior to tempering there was no discernable trend. However, tempered wheat from different treatments equilibrated to the same moisture content ($F = 1.17$; df = 6, 14; $P = 0.3734$). The effect of infrared radiation on kernel hardness and kernel moisture is obvious by observing the frequency distribution of these parameters (Figs. 1 and 2). The kernel hardness frequency distributions were less variable than kernel moisture distributions. The kernel moisture was affected to a greater extent when 113.5 g of wheat was exposed to infrared radiation compared with 227.0 g of wheat. However, tempering resulted in both kernel hardness and the moisture distributions of infrared-exposed wheat approximating to that of untreated wheat.

The flour yield, bran yield, and flour loss (Table 3) during milling were all significantly different among the treatments ($F$ range among quality factors = 2.91–3.65; df = 6, 14; $P \leq 0.0469$). The flour lost during milling was about 6–9%. However, the yield of shorts was not significantly different among the treatments ($F = 2.73$; df = 6, 14; $P = 0.0572$).

The flour particle diameters of untreated wheat were slightly smaller than particles from infrared-treated wheat (Table 4). About 90% of the flour particles in untreated wheat were below 116 μm,

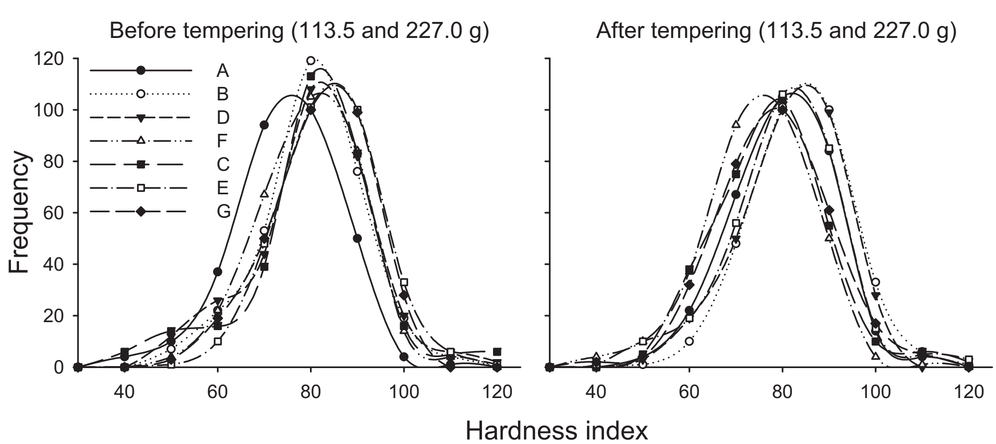


**Fig. 1.** Frequency distribution of kernel hardness of wheat not exposed to infrared radiation (A), and 113.5 g (B, D, F) or 227.0 g (C, E, G) of wheat exposed to infrared radiation for 45 (B, C) or 60 s (D, E, F, G). See Table 1 for additional treatment information.

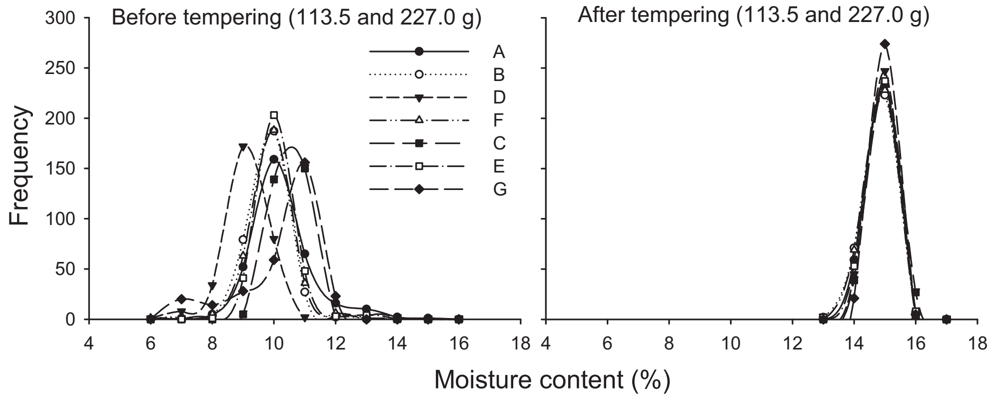


**Fig. 2.** Frequency distribution of moisture content of wheat not exposed to infrared radiation (A), and 113.5 g (B, D, F) or 227.0 g (C, E, G) of wheat exposed to infrared radiation for 45 (B, C) or 60 s (D, E, F, G) before and after tempering. See Table 1 for additional treatment information.

whereas particles from infrared-treated wheat ranged from 120 to 126 μm. However, these differences were not significant ($F = 2.58$; df = 6, 14; $P = 0.0672$). The differences in sizes of 10% and 50% of the particles among treatments were smaller than sizes for 90% of the particles. However, significant differences among treatments in particle sizes at both these percentages were detected ($F$ range = 3.35–4.17; df = 6, 14; $P \leq 0.0291$).

The bran contamination of flour, based on Agtron spectrometer output, was not significantly different among the treatments ($F = 2.23$; df = 6, 14; $P = 0.1013$). The Agtron reflectance units among treatments ranged from 64.3 to 67.0.

The moisture content of flour ranged from 13.2 to 14.0% among the treatments (Table 5) but these differences were not significantly different from one another ($F = 2.30$; df = 6, 14; $P = 0.094$). The ash content values were rounded off to one decimal place in the table, but the actual values among treatments ranged from 0.56 to 0.63%. The protein content differed by 0.1–0.2% among treatments. However, the flour ash and protein values were different among the treatments ($F$ range = 4.24–4.32; df = 6, 14; $P < 0.0122$), and the differences observed did not follow any pattern. The moisture and ash of shorts, and ash of bran, were significantly different among the treatments ($F$ range = 3.64–6.73; df = 6, 14; $P \leq 0.0216$). The protein content of both shorts and bran, and bran moisture and total starch were not different among the treatments ($F$ range = 1.40–2.71; df = 6, 14; $P \geq 0.0584$). In cases where differences were observed, there were no discernable trends.

The falling number value for untreated wheat flour was 537.3 and similar values were obtained for infrared radiation-treated flour, 557.0 to 592.3; differences among treatments were not observed ($F = 0.95$; df = 6, 14; $P = 0.4927$). Mixograph results show both water absorption and mixing time to be different among the treatments ($F$ range = 4.53–5.83; df = 6, 14; $P \leq 0.0032$) (Table 6). The bake test results (Table 7) showed that the baking absorption values, mixing time, and loaf volume varied significantly among the treatments ($F$ range = 3.13–4.53; df = 6, 14; $P \leq 0.0369$). However, the trends did not show a consistent pattern.

## 4. Discussion

The test weights of hard red winter wheat varieties in the USA range from 73.7 to 83.2 kg/hl (Maghirang et al., 2006). The test weight of untreated and infrared-treated wheat in our study was 79–81 kg/hl. Maghirang et al. (2006) reported that wheat grain test weights greater than 71.7 kg/hl are correlated with higher flour extraction potential. The lower kernel hardness values of infrared-exposed wheat relative to untreated wheat may be purely a result of moisture loss upon infrared exposure. The frequency distributions of kernel moisture and hardness support this view. Loss of moisture from infrared-exposed wheat is expected, because infrared radiation, especially in the 3–7 μm range is used for drying grains (Pan et al., 2008). This drying effect could have reduced both the flour and bran yield and increased flour loss during milling, and may have resulted in the larger particle sizes observed. Flour yield is influenced by many factors such as milling conditions, condition of the machine, and type of wheat (Maghirang et al., 2006). Flour

**Table 3**
Milling yields of wheat fractions and flour yield loss in various treatment combinations.

| Treatment | Mean ± SE (%)[a] | | | |
|---|---|---|---|---|
| | Flour | Bran | Shorts[b] | Loss |
| A | 68.3 ± 0.8a | 17.5 ± 0.7a | 8.3 ± 0.3 | 6.0 ± 0.4b |
| B | 68.0 ± 0.6ab | 15.7 ± 1.3ab | 9.0 ± 0.6 | 7.3 ± 0.6ab |
| C | 67.5 ± 0.7ab | 16.8 ± 0.6ab | 9.3 ± 0.4 | 6.4 ± 0.5b |
| D | 66.8 ± 0.7ab | 16.3 ± 0.5ab | 9.3 ± 0.2 | 7.6 ± 1.0ab |
| E | 65.2 ± 0.7b | 16.7 ± 0.7ab | 9.1 ± 0.3 | 9.1 ± 0.3a |
| F | 67.1 ± 0.2ab | 15.2 ± 0.5ab | 9.6 ± 0.1 | 8.1 ± 0.3ab |
| G | 66.3 ± 0.7a | 13.3 ± 1.0b | 10.0 ± 0.3 | 8.4 ± 0.7ab |

[a] Means within a column followed by different letters are significantly different ($P < 0.05$, REGWQ test).
[b] Means among treatments were not significantly different from one another ($P > 0.05$, one-way ANOVA).

**Table 4**
Particle size distribution of flour from unexposed and infrared-exposed wheat.

| Infrared treatment ID | Mean ± SE percentage of particles below a certain diameter (μm) | | |
|---|---|---|---|
| | 10[a] | 50[a] | 90[b] |
| A (Control) | 12.6 ± 0.1b | 49.6 ± 0.5b | 115.8 ± 1.6 |
| B | 13.3 ± 0.1ab | 53.5 ± 0.2ab | 120.1 ± 1.2 |
| C | 13.0 ± 0.3ab | 52.2 ± 1.8ab | 120.1 ± 1.6 |
| D | 13.7 ± 0.3a | 56.5 ± 2.3a | 125.6 ± 3.5 |
| E | 13.6 ± 0.1a | 56.5 ± 0.6ab | 122.3 ± 0.0 |
| F | 13.5 ± 0.0a | 54.0 ± 0.5ab | 119.8 ± 1.0 |
| G | 13.5 ± 0.0a | 54.0 ± 0.3ab | 120.5 ± 0.6 |

[a] Means within a column followed by different letters are significantly different ($P < 0.05$, REGWQ test).
[b] Means among treatments were not significantly different from one another ($P > 0.05$, one-way ANOVA).

**Table 5**
Proximate analysis values for flour, shorts and bran from unexposed and infrared-exposed wheat.

| Fraction | Treatment | Mean ± SE (%)[a] | | | |
|---|---|---|---|---|---|
| | | Moisture | Ash | Protein | Starch |
| Flour | A | 14.0 ± 0.3c | 0.6 ± 0.0a | 12.0 ± 0.0a | –[b] |
| | B | 13.2 ± 0.2 | 0.6 ± 0.0a | 11.8 ± 0.0b | – |
| | C | 13.9 ± 0.3 | 0.6 ± 0.0ab | 12.0 ± 0.0ab | – |
| | D | 13.4 ± 0.2 | 0.6 ± 0.0ab | 11.8 ± 0.0ab | – |
| | E | 13.6 ± 0.3 | 0.6 ± 0.0b | 11.8 ± 0.0a | – |
| | F | 13.5 ± 0.2 | 0.6 ± 0.0a | 11.9 ± 0.0ab | – |
| | G | 13.4 ± 0.2 | 0.6 ± 0.0ab | 11.8 ± 0.0ab | – |
| Shorts | A | 11.4 ± 0.1a | 2.7 ± 0.1c | 14.6 ± 0.2[c] | – |
| | B | 10.6 ± 0.1b | 3.1 ± 0.1a | 15.3 ± 0.0 | – |
| | C | 11.3 ± 0.3ab | 2.7 ± 0.0bc | 15.2 ± 0.5 | – |
| | D | 10.6 ± 0.1b | 2.9 ± 0.1abc | 15.1 ± 0.2 | – |
| | E | 11.2 ± 0.1ab | 2.7 ± 0.0c | 14.5 ± 0.1 | – |
| | F | 11.1 ± 0.1ab | 3.0 ± 0.1abc | 14.6 ± 0.1 | – |
| | G | 10.9 ± 0.0ab | 3.1 ± 0.0ab | 15.3 ± 0.0 | – |
| Bran | A | 13.7 ± 0.2[c] | 5.3 ± 0.1ab | 17.1 ± 0.1[c] | 15.2 ± 0.4[c] |
| | B | 12.8 ± 0.2 | 5.3 ± 0.0a | 16.3 ± 0.1 | 15.8 ± 0.4 |
| | C | 13.3 ± 0.3 | 5.3 ± 0.0ab | 16.9 ± 0.1 | 16.7 ± 0.1 |
| | D | 12.7 ± 0.2 | 5.3 ± 0.0ab | 16.6 ± 0.2 | 16.9 ± 0.3 |
| | E | 13.2 ± 0.1 | 5.2 ± 0.0ab | 16.4 ± 0.3 | 15.4 ± 0.6 |
| | F | 13.3 ± 0.5 | 5.4 ± 0.0ab | 16.6 ± 0.2 | 15.5 ± 0.8 |
| | G | 13.0 ± 0.3 | 5.4 ± 0.0a | 16.5 ± 0.2 | 14.4 ± 1.0 |

[a] For each fraction, means within a column followed by different letters are significantly different ($P < 0.05$, REGWQ test).
[b] Starch values were determined only for bran.
[c] Means among treatments were not significantly different from one another ($P > 0.05$, one-way ANOVA).

yields among the treatments were within the range stated by the Buhler Mill manufacturer (64–70%). However, rehydration during tempering normalized the moisture contents of infrared-treated wheat to that of untreated wheat. Therefore, changes in kernel moisture and hardness upon infrared exposures were reversible for all treatment combinations. Osborne et al. (1997), Osborne and Anderssen (2003), and Ohm et al. (1998) reported that kernel hardness is directly related to flour yield and quality.

Equilibration of grain moisture contents during tempering perhaps did not result in any bran contamination of the flour. Whole wheat has 9.2–15.8% protein (Maghirang et al., 2006). A 1% loss of protein through the bran and shorts during milling is expected (Halverson and Zeleny, 1988). Flours desirable for bread-making should have between 11 and 12% protein, and despite minor differences, the protein contents among the treatments were close to 12%. Shorts are composed of some bran and germ. Ash content is 10 times greater in bran than in flour. Bakers normally specify flour ash content of 0.48–0.52%, and the ash content in our flour averaged around 0.6%, close to commercial specifications. Despite differences in some chemical constituents in flour, shorts, and bran, the lack of consistent trends makes it difficult to explain the statistical differences observed.

**Table 6**
Water absorption values and mixing times for flour from unexposed and infrared-exposed wheat.

| Treatment | Mean + SE[a] | |
|---|---|---|
| | Water absorption (%) | Mixing time (min) |
| A | 68.7 ± 0.3ab | 3.8 ± 0.0ab |
| B | 67.3 ± 0.3c | 3.8 ± 0.2ab |
| C | 68.3 ± 0.3abc | 3.7 ± 0.1ab |
| D | 67.7 ± 0.3bc | 3.7 ± 0.2ab |
| E | 69.0 ± 0.0a | 4.5 ± 0.5a |
| F | 68.0 ± 0.0abc | 3.0 ± 0.3b |
| G | 67.7 ± 0.3bc | 2.8 ± 0.0b |

[a] Means within a column followed by different letters are significantly different ($P < 0.05$, REGWQ test).

**Table 7**
Water absorption values, mixing times, and loaf volumes for flour from unexposed and infrared-exposed wheat.

| Treatment | Mean ± SE[a] | | |
|---|---|---|---|
| | Water absorption (%) | Mixing time (min) | Loaf volume (cc) |
| A | 72.7 ± 0.3ab | 3.5 ± 0.0ab | 995.0 ± 17.3a |
| B | 71.4 ± 0.3c | 3.6 ± 0.2ab | 873.7 ± 22.7ab |
| C | 72.4 ± 0.3abc | 3.5 ± 0.1ab | 959.0 ± 3.5ab |
| D | 71.7 ± 0.3bc | 4.2 ± 0.6a | 822.7 ± 71.4b |
| E | 73.1 ± 0.0a | 4.4 ± 0.6a | 860.0 ± 50.6ab |
| F | 72.1 ± 0.0abc | 3.0 ± 0.3ab | 954.3 ± 5.8ab |
| G | 71.7 ± 0.3bc | 2.6 ± 0.1b | 924.7 ± 11.7ab |

[a] Means within a column followed by different letters are significantly different ($P < 0.05$, REGWQ test).

Falling numbers for wheat flour have been reported to range from 278 to 861 (Maghirang et al., 2006), and the falling numbers observed in this study fell within these ranges. The higher falling number values for infrared-treated wheat compared with that for untreated wheat, despite the lack of significant differences, may suggest that exposing wheat to infrared radiation may have inactivated the alpha amylase enzyme. Falling number values below 278 may indicate sprout damage or increased enzymatic activity (Atwell, 2001).

In the United States a mixograph is commonly used for evaluating physicochemical properties of dough and bread-making potential (Ingelin and Lukow, 1999; Maghirang et al., 2006). Desirable flours should have water absorption in the range of 62–66%, and the flours from untreated and infrared-treated wheat in our study averaged about 68%. Good flour from hard red winter wheat should have 3–3.5 min of mixing time since it has a positive correlation with dough proof height and volume (Maghirang et al., 2006). Flour from infrared-treated wheat and untreated wheat had a moderate mixing time. Moisture absorption during baking was slightly higher than the flour absorption, probably due to inclusion of other additives during baking. However, the flour and bake mixing times were essentially similar. Maghirang et al. (2006) reported baking absorption, mixing time, and loaf volume for hard red winter wheat cultivars to be 58.2–66.4%, 2.33–6.75 min, and 685–1060 cc, respectively. The baking absorption values in our study fell outside this range, but the mixing time and loaf volumes were well within ranges specified by Maghirang et al. (2006). Although several physical, chemical, and rheological parameters were statistically different among untreated and infrared-treated wheat samples, the differences observed were not too large to be of any practical concern. Our results suggest that infrared radiation used for disinfesting stored wheat, under our test conditions, did not adversely affect wheat's physical, chemical, rheological, or end-use qualities.

## Acknowledgments

The research reported here was supported by funds from a USDA/CSREES NC-IPM grant. All quality analyses were conducted in the Department of Grain Science and Industry's Wheat Quality Laboratory, under the supervision of Dr. Rebecca Miller. This paper is contribution 11-122-J from the Kansas State University Agricultural Experiment Station.

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